Confirmation of the Wave Nature of Electrons via the Ramsauer-Townsend Experiment

Nathaniel Herbert

Physics Department, University of Texas at Austin

Abstract

Our experiment demonstrates the Ramsauer-Townsend effect by showing that a sudden dip in collision potential between electrons and xenon atoms occurs at what is known as a critical voltage for electrons at low energies. This phenomenon is unexplainable through classical laws of physics and requires the rework and improvement of the current model of modern physics. The accepted value for the electron's critical voltage at which the Ramsauer-Townsend effect occurs is 1 electron-volt. Our value of $.97 \pm .06$ eV, differs by 2.83%. Using the error analysis from our experiment, the accepted value is incorporated in our results. This phenomenon leads to the unavoidable conclusion that electrons do not behave like billiard balls at the quantum level and a wave nature must be introduced in order to explain these classically unexpected results.

1 Introduction

1.1 Physics Motivation

The Ramsauer-Townsend Experiment is an important demonstration into the quantum nature of electrons, the properties which they possess, and a practical insight into applications for circuits at the quantum level. [1] The effect is named after Carl Ramsauer (1879-1955) and John Sealy Townsend (1868-1957), who each independently studied the collisions between atoms and low-energy electrons in the early 1920s.

The main purpose of this experiment is that it demonstrates the need for physical theories more sophisticated than those of classical physics. These theories in turn lead to greater insight into the fundemental properties of matter. Theories such as quantum tunneling and quantum field theory would be nothing more than ideas without solid evidence of wavelike behavior in particles.

1.2 Theoretical Background

If one tries to predict the probability of a collision between an electron and an atom with a classical model that treats the electron and atom as hard spheres, one finds that the probability of collision should continually decrease with increasing electron energy. [2] However, Ramsauer and Townsend observed that for slow-moving electrons in argon, krypton, or xenon, the probability of collision between the electrons and gas atoms plummets towards zero at an experimentally determined critical voltage. [3] This is the Ramsauer-Townsend effect. This effect can not be explained by the classical picture of particle collisions. It is from this experiment that clear evidence for the wave aspect of electrons was be obtained.

The potential energy of an electron inside an atom can, to some extent, be approximated as a square well with a uniform depth V_0. [4] Noble gases fit this approximation well, since they have no free electrons, their outer valence electrons are bound very tightly. [5] If an electron traveling in an electron beam interacts with a group of atoms it will confront this potential well. The wavelength of the electron would then change from $\lambda_1 = \frac{h}{p_1} = \frac{h}{\sqrt{2mE}}$ to $\lambda_2 = \frac{h}{p_2} = \frac{h}{\sqrt{2m(E-V_0)}}$. [6]

Because of this sudden change, part of the wave is transmitted, and part of the wave is reflected. The transmitted wave then continues to the edge of the potential well where it interacts with a second boundary, and partial transmission and reflection occurs again. This is demonstrated in figure 1.

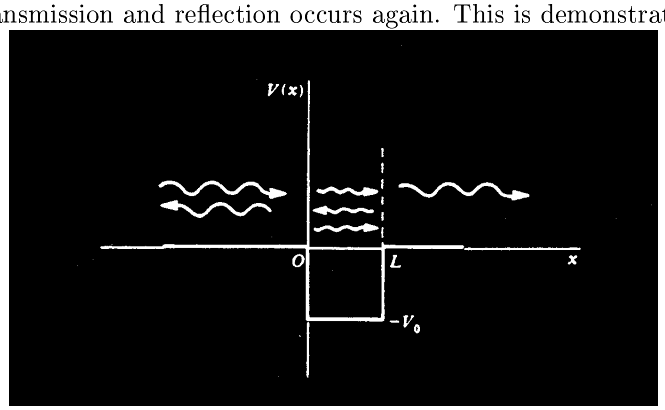

Figure 1: Demonstration of Reflection and Transmission in a Square Well

The next step is to see if one could get the wave to reflect at the boundaries to achieve 100% transmission. This occurs when the well size is equal to half of the wavelength of the particle in the well. The wave reflected at the end of the potential will travel a half wavelength and by the time it reaches the front of the potential well again it recombines with the new incoming wave to constructively interfere. When this condition is met, there is 100% transmission of the incident wave. The total effect of this is that at the correct velocity, the electron wave effectively does not see the atom, and passes through this region unaffected.

1.3 Our Approach

In the Ramsauer-Townsend experiment, an electron beam originates from a cathode in the first section of the apparatus. The beam of electrons passes through the second section where some of the electrons are scattered by the xenon atoms and collected on the shield and the rest are collected on the plate that is located in the third section. To measure control effects, the xenon is then frozen out with liquid nitrogen. This creates a control group because freezing the xenon causes it to sink into the bottom of the chamber. This has the effect of reducing the probability of scattering to approximately zero.

2 Experimental setup

2.1 Apparatus

There are two major components to the setup of this experiment. First there is the 2D21 thyratron tube where the major part of the experiment occurs. A beam of electrons is fired from the cathode, and accelerated toward the collection plate on the other side of the chamber. In the center of the chamber, some of the electrons collide with xenon gas which causes them to scatter in essentially random directions. These electrons that collide with the xenon atoms are then collected onto the shields located on the sides of the thyratron tube. The electrons that are not scattered continue on their path to the plate. Currents from both the shield and the plate are collected and denoted I_s and I_p respectively. See figure 2.

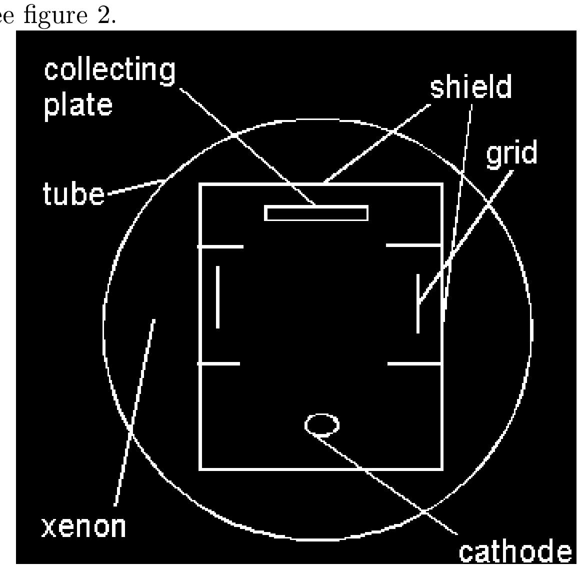

Figure 2: Thyratron Tube Setup

The second part of this experiment contains the setup of the circuits that allow the electrons to be manipulated properly. Two Tenma DC power supplies were used, the first one was attached to the cathode/anode circuit in order to accurately be able to manipulate the energy levels of the electron beam. The second power supply was connected to the filament heater and was set to about 4 V in order to keep temperature within the thyratron tube constant between trials. See Figure 3 for a detailed picture.

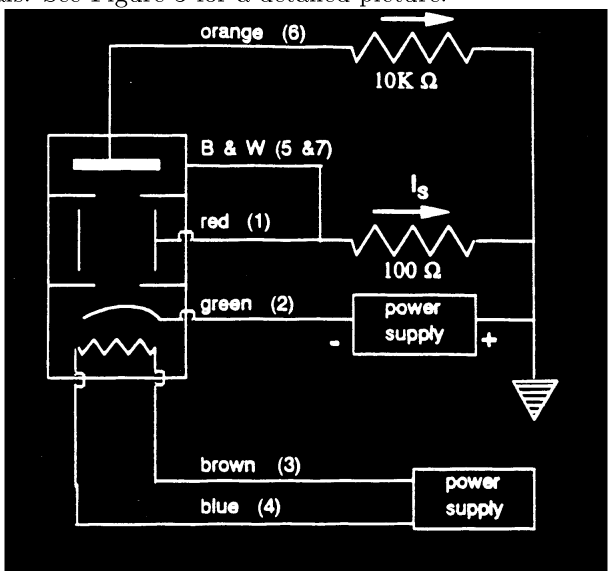

Figure 3: Circuit Setup

2.2 Data Collection

The procedure for this experiment was relatively simple. A potential was applied across the thyratron tube. and varied form 0 to 10 volts. This potential had the affect of accelerating the electrons through the tube. For each value of accelerating potential, a value for plate and shield potential were also obtained. The plate potential was a measure of how many electrons made it through the cloud of xenon gas without suffering a collision (it also includes the electrons that collided with the xenon and scattered in the forward direction to be collected by the plate), while the shield potential was a measure of the electrons that were scattered by the xenon atoms.

All of this data was collected through LabVIEW, the only variation being the accelerating voltage which had to be varied manually.

This procedure was repeated three times with the xenon at a standard room temperature, and three times with the xenon frozen by liquid nitrogen.

3 Data Analysis and Results

3.1 Data Processing and Hypothesis Testing

As sighted by the Kukolich guide provided by the lab manual for this experiment [7], the probability of electron scattering is given by

$$P_s = 1 - \frac{I_s^* I_p}{I_s I_p^*} \tag{1}$$

where $I_s$is the shield current, I_p is the plate current, and the*represents the respective frozen current values.

By plotting a graph of probability of a collision as a function of accelerating voltage it is very clear to see that the probability of collision decreases as a function of accelerating voltage. This is exactly as predicted by a classical approach. There is however, a brief moment where the probability plummets towards zero and then continues on its predicted course. This is a clear indication of the Ramsauer-Townsend Experiment. Figure 4 shows one of our sample runs at room temperature.

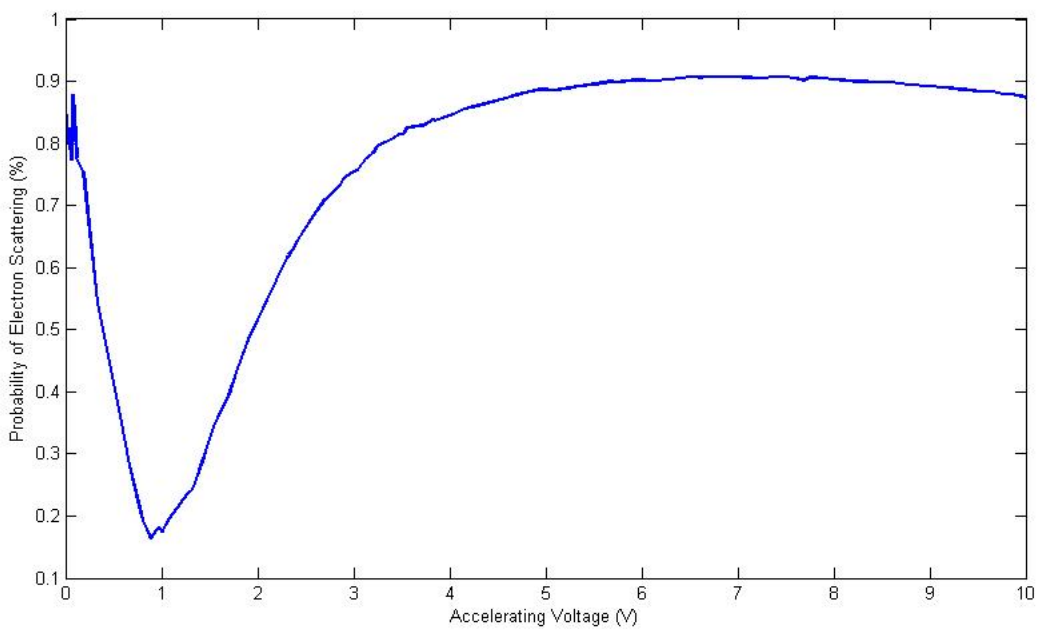

Figure 4: Plot of Probability of Collision as a Function of Accelerating Voltage

Another graph which clearly shows the quantum effect of electron scattering is the graph of the plate currents at liquid nitrogen temperatures and at room temperature as a function of the accelerating potential. If the Ramsauer-Townsend effect was not occurring then one would expect the shapes of the two graphs to be approximately the same, however it is clear from figure 5 that the graph of the plate current at room temperature deviates tremendously due to the effect.

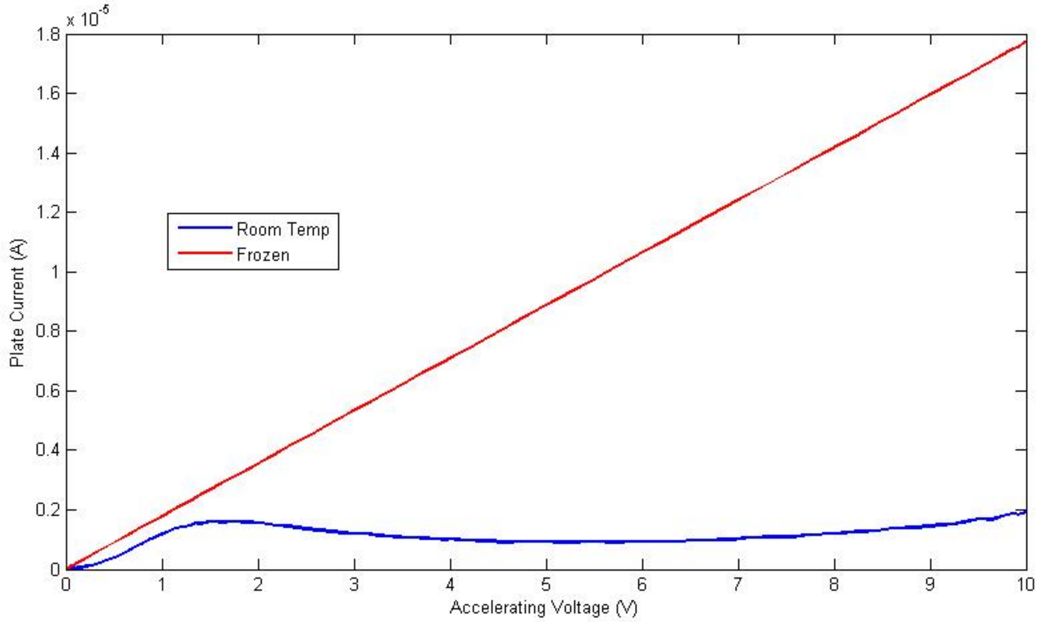

Figure 5: Plate Current as a Function of Accelerating Voltage

3.2 Results and Brief Discussion

By combining the data for the critical voltages from all three of our room temperature trails and averaging them, we obtain a value of .97±.06 eV for our critical voltage. The only real measurable sources of error in this experiment come from the slight variations in voltage and the inaccuracies of the two Tenma DC power supplies. Although I am sure there are rounding errors and accuracy errors in LabVIEW, unfortunately there is no way to measure this and I am left only with speculations. However, considering our result is so accurate, I will consider the errors of LabVIEW minimal.

4 Summary and Conclusion

The accepted value for the electron's energy at which the Ramsauer-Townsend effect occurs is 1eV. Our value which is .97±.06 eV, differs by 2.833%. The error bars of our experiment incorporates this accepted value. (This is the very first experiment for me which this has happened!)

This is a surprisingly accurate result for all of the things that could have gone wrong in a junior lab. Contributions from the shield current may have interfered with the current on the plate in some way, LabView may have miscalculated values or had a precision that was insufficient, internal resistance of the wires should have contributed some error. This is to name a few of the multiple sources of error and ways this experiment could have gone wrong.

Although our experimental value is excellent compared to the accepted value for the critical voltage, attention should not be focused on the actual values obtained, but more so on the importance of the shape of the data. It is extremely clear that at some critical voltage, the scattering potential of the electrons plummets towards zero. That is the most important point in this experiment, because it shows that the Ramsauer-Townsend Effect is occurring. This is evidence for the failure of the classical model which predicts a consistently decreasing scattering potential for an increasing acceleration potential.

In conclusion, these effects were found to be best explained by the wave nature of electrons. When the electrons had an energy such that their wavelengths were equal to half the diameters of the xenon atoms, the partial reflections at the two surfaces of the atom acted to constructively interfere with each other, effectively allowing the electron waves to travel straight through the atoms and transmit completely.

I would like to thank Spencer Jolly my TA for helping me and my partner with our project. I would especially like to thank my partner in this experiment Jim Pharr for his incredible help in both the lab and with my understanding of MatLab. Lastly, I would like to thank you, the grader, for taking the time to check my work and helping expand my knowledge of writting lab reports.

5 References

[1] Duane, S (2010) On the Ramsauer-Townsend Effect, SF Theoretical Physics

[2] Albers, A (2005) Quantum Scattering and a Determination of the Scattering Cross-Section of Xenon Gas in a 2D21 Thyratron Tube

[3] Madison, L (2005) Ramsaur - Townsend Effect, University of Wisconsin

[4] Brown, J. The Schrodinger Equation in One Dimension. New York: Random House, 2003

[5] Helmenstine, A (2007) On Nobel Gases

[6] Zimmerman, A (2004) De Broglie Hypothesis

[7] Kukolich, S (1968) Demonstration of the Ramsauer-Townsend Effect in a Xenon Thyratron, Department of Physics Massachusetts Institute of Technology